Scale-free dynamics of rainfall

1 Rainfall scales

Rainfall is a ubiquitous phenomenon that connects processes ocurring on many different spatial, temporal, and energetic scales. Depending on the level of coarse graining applied by different observational techniques, the nature of the process changes considerably. Microscopically, rainfall consists of raindrops with a diameter no larger than a few mm and fall velocities of a few m/s, or to make this point clearer, a few million mm/h. Typically, we think of rain fields with a spatial extent of many km, occasionally up to thousands of km. Measured rain intensities rarely exceed 100 mm/h; a light drizzle corresponds to about 1 mm/h. Temporally, the arrivals of idividual drops last about 1 ms, whereas coherent rain events can last several hours, even up to days.
Depending on the method of measurement we observe rainfall at different scales. 2×2 degree satellite observations will not reveal rainfall at 300 mm/h, neither will hourly resolved tipping-bucket data. Optical gauges recording the passing of indiviual drops lead to an atomistic representation. In general the scales of temporal and spatial resolution as well as instrument sensitivity will change our impression of what rainfall is. Globally, it rains continuously at about 0.1mm/h. But intermittency is introduced at smaller scales – in northern Germany it rains about 5% of the time on a minute-resolved basis in an area of 100 m^2. This simple glance at the different scales involved in rainfall already suggests similarities to a critical process. Critical opalescence is an example of interactions between individual atoms leading to coherent (light-scattering) structure on scales three orders of magnitudes larger.

2 Self-organized criticality (SOC) and rainfall

SOC models are generally defined on lattices, discrete in space and time. They are driven by adding a particle to a lattice site. When a lattice site reaches a threshold number of residing particles, it dissipates them instantaneously to its neighbours. These may in turn reach their particle thresholds and consequently topple. In this manner an avalanche can be started. The avalanche finishes when no site harbors more particles than maximally allowed by its threshold value. Subsequently, the model is driven again. Particles are conserved within the bulk and dissipated at the boundaries, implying diverging event sizes in the thermodynamic limit.

The atmospheric system has all the generic properties of SOC systems. It is slowly driven by solar radiation, that is, water vapor is being pumped into the atmosphere at a low rate. The water is stored here intermediately, but there exist local thresholds of energy (or water) density that lead to condensation, triggering the highly complex mechanisms of precipitation production. The energy release mechanism is fast and organized in bursts, rain showers.
The analogy to critical systems is supported by evidence of scale-freedom over several orders of magnitude [3, 2]. Choosing observational scales fine enough for rainfall to be intermittent and coarse enough for there to be events of a range of magnitudes and durations, we find that the released water columns during events (defined as a sequence of non-zero measurements of rainfall intensity) follow a power-law probability distribution – according to recent (unpublished) data over up to five orders of magnitude, see Fig. 1. Event duration distributions also show signs of scale-freedom, as do the waiting time distributions between events. I'm in close contact with the experimentalists from the Max-Planck Institute for Meteorology as well as the Meteorological Institute in Hamburg, who developed the powerful observation techniques and generously provide me with data.

Rainfall is a beautiful example of a self-organized

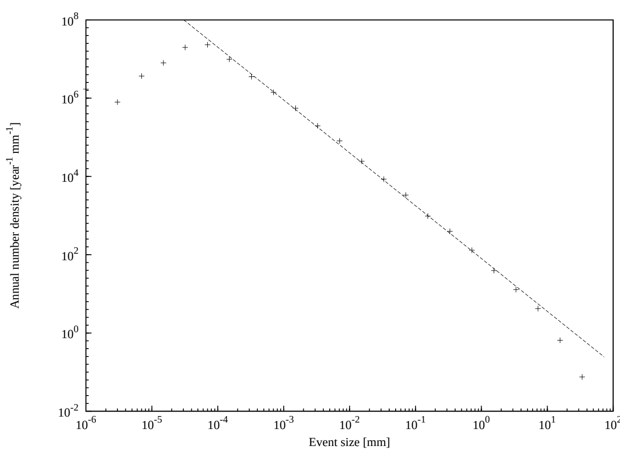

Figure 1: Log-log plot of the rain event size distribution. Data from 1/2 year micro rain radar (MRR) measurements in Westermarkelsdorf, German Baltic Sea coast. The annualised number density $p(s)$ falls off with events size s as a power law $p(s) \propto s^{-\tau}$, with $\tau \approx 1.35$ over about 5 orders of magnitude in event size.

critical process. Questions regarding the rôle of time scales which cannot be answered with standard SOC models (because time-scales are ill-defined here) can be addressed both experimentally and in modelling

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efforts. An analysis of the Ising model suggests that the choice of parameters controlling time scales has a profound impact on the observed scaling behavior of the system [4]. Further studies of rainfall may help identify universal properties in self-organizing systems. It is known, for example, that some scaling exponents are more robust than others to changes in the dynamical rules of SOC models [1].

3 Large-scale modelling and rainfall microstructure

Rainfall is often modelled as a direct consequence of convection events. But it is obvious that there is much more structure to it than just convection. Rainfall self-organizes, it shapes its own environment as drops fall, merge, break up, evaporate and leave trails of moisture. Our observations show that there might be a universal self-organization process involved affecting all relevant scales. The overall dynamics of rainfall are determined in part by microstructure and partly by convective forcing. Comparison between convection dynamics and rainfall dynamics will verify the significance of self-organization.

It has been observed in direct measurements that convectional available potential energy (CAPE), the energy that lifts air moist air masses by convection, has a $1/f$ power spectrum, compatible with long-time correlations. It has also been observed that the introduction of strongly temporally correlated noise terms in the (exponential) models of the decay of CAPE leads to more realistic rainfall distributions in climate models. The observed type of correlation can be reproduced with simple SOC models, providing a physical basis for implementing long-range correlation in models of the world's weather and climate. I'm currently working on implementing realistic noise terms, as well as CAPE-decay functions in a model developed in the Department of Atmospheric and Oceanic Sciences at UCLA.

References

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